The WFIRST Coronagraph Instrument – An update

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Mirror Tech Workshop
Redondo Beach – 16 November 2016

The WFIRST Coronagraph Instrument is designed for the exploration of exoplanet systems

- WFIRST hosts two instruments: the Wide Field Imager (WFI) emphasizing dark energy investigations, and the coronagraph instrument (CGI) to advance the technologies for ***extreme high contrast imaging*** and spectroscopy from space.
- Paves the way for ***future exo-Earth imaging missions*** now envisioned as the HabEx and LUVOIR concepts.
- Mature planets are seen in ***reflected starlight***, and are ***faint*** and ***close to the star*** (relative intensities are parts per billion, separations are tenths of an arcsecond).
- The mission is intended to advance the essential technologies for control of the ***complex (amplitude and phase) wavefront to picometer levels*** with a 2.4 meter space telescope.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

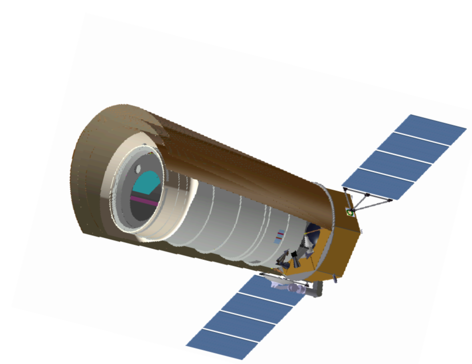
WFIRST inherits recent coronagraph technology developments

- ***WFIRST is intended to advance observatory performance models and validate them against actual on-orbit performance***.

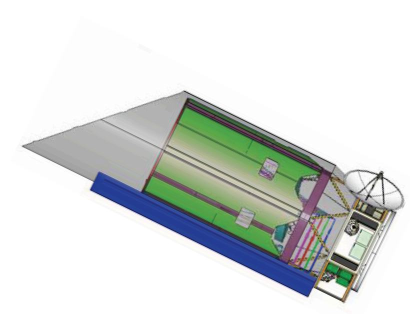
- *The **CGI design is a distillation of knowledge gained** from the past decade of science mission concept studies and ground-based experience.*
  - *Space mission studies for groundbreaking exoplanet science (Astrophysics Strategic Mission Concept Studies/ACCESS, PECO, EPIC, 2009) and the Exo-C mission concept study (2015).*
  - *Technology developments (NASA/SAT/TDEMs for space coronagraphs)*
  - *Direct imaging experience (GPI, SPHERE, SCExAO/CHARIS) from ground-based observatories.*

- ***The CGI establishes a pioneering foothold** in direct imaging of exoplanet systems, validating science performance predictions while providing a science baseline for future exoplanet mission planning.*

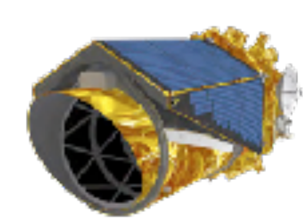
Ground Observatories



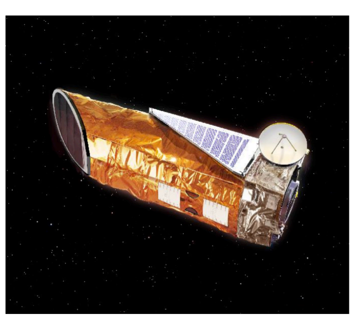
Concept studies: ASMCS/ACCESS



ASMCS/PECO



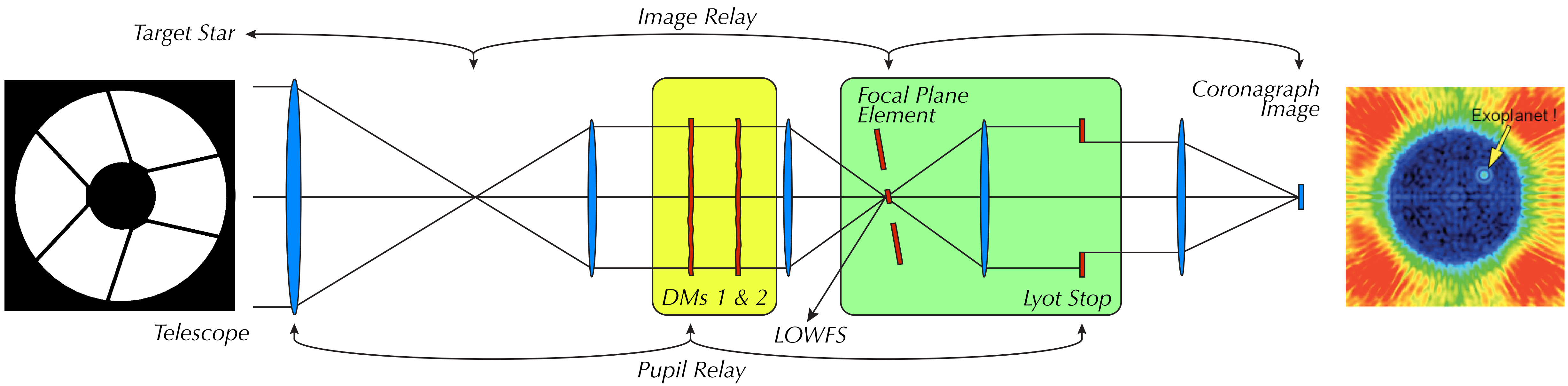
ASMCS/EPIC



Exo-C

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

An actively corrected coronagraph

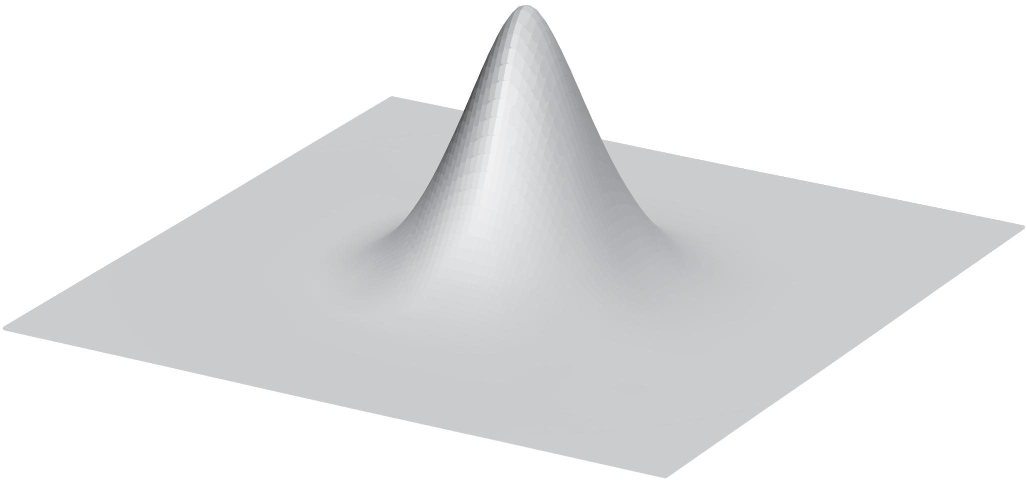


- Sketch of the essential elements of an ***actively corrected Lyot coronagraph*** includes
  - the ***pair of deformable mirrors for control of the complex wavefront*** to create the high contrast dark field of view, correct for telescope static wavefront errors, compensate for thermal drift in the telescope optics, and
  - the ***coronagraph elements to suppress starlight diffracted by the telescope*** (HLC shown here, comparable diagrams describe the Shaped Pupil coronagraphs).
- Coronagraph ***design is matched to our current knowledge of the WFIRST telescope***. These have evolved (and continue to evolve) as we learn more about the WFIRST static and dynamic wavefront characteristics.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Wavefront control with deformable mirrors

Xinetics 48x48 DM (2304 actuators on a 1x1-mm pitch)



Single actuator influence profile

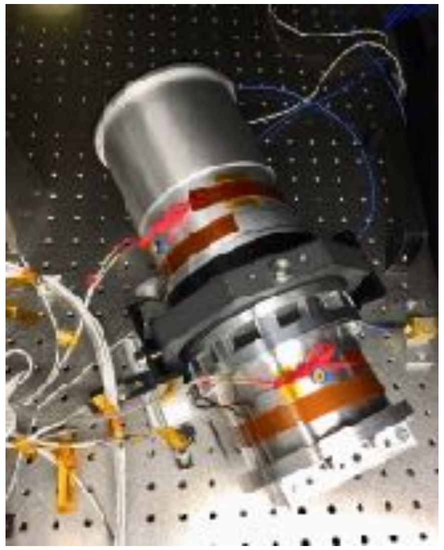
- WFIRST coronagraph design incorporates a ***pair of 48x48-actuator deformable mirrors (DMs).***
- Developments of DM hardware and control algorithms over the past decade have enabled ***high contrast demonstrations*** in the laboratory, as documented by NASA-sponsored ASMCS, TDEM, TPF-C, and recent WFIRST coronagraph milestones.
- WFIRST program is intended to ***extend past developments*** by maturing manufacturing processes, carrying out a flight qualification environmental test program, and detailed calibrations on the path to Technology Readiness Level TRL9.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Characterizations of the deformable mirrors

- *Laboratory* ***Vacuum Surface Gauge (VSG)*** *is an imaging interferometer mounted within a vibration-isolated vacuum chamber.*
- *VSG images the DM surface with 250 pixels / mm^2, measures individual actuator strokes to 50 pm rms with background/parasitic signals < 1%.*
- *It is being used to* ***characterize flight-like 48x48 engineering DMs****. Our objectives are:*
  - *Measure surface influence profiles and calibrate surface .*
  - *Characterize stability, drift, and hysteresis to picometer rms levels in response to voltage transitions.*
  - *Develop and demonstrate DM surface control algorithms to match flight operational requirements.*
- *Xinetics 48x48 engineering DMs are being characterized in the VSG as part of the program to advance to* ***TRL6.***

VSG is certified for JPL critical items.



48x48 DM mounted in the VSG

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

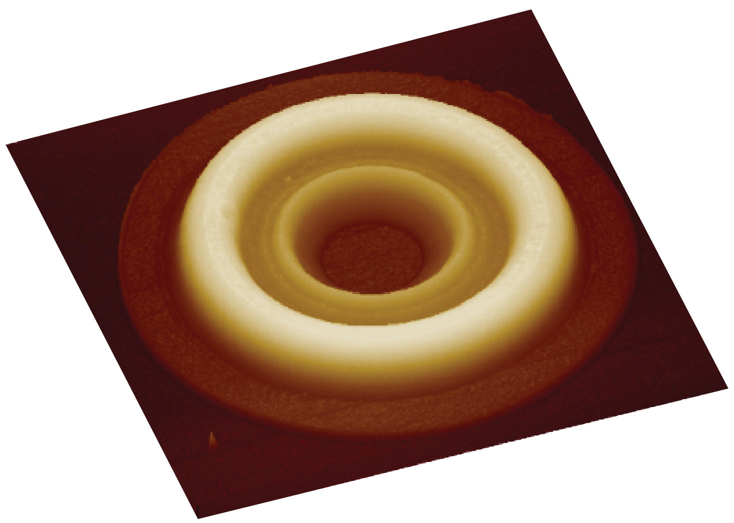
WFIRST coronagraph wavefront control

- Wavefront stability requirements exceed those of the WFIRST observatory, therefore ***sensing and correction of wavefront errors and jitter*** are implemented within the WFIRST coronagraph.

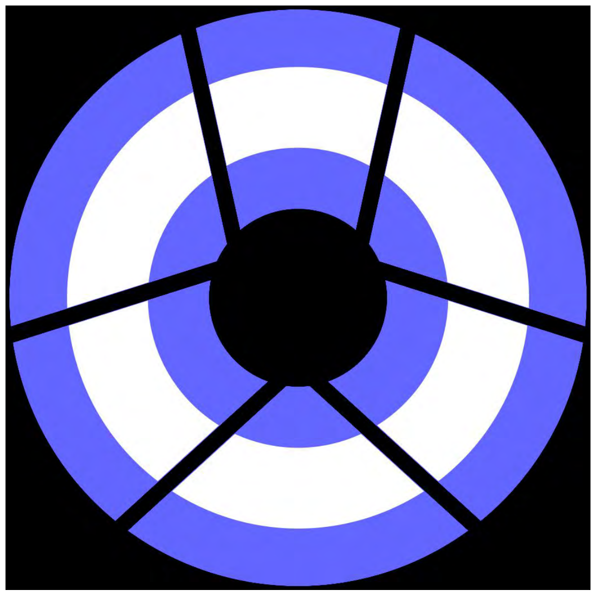
- ***Response to pointing control requirements:*** (1) coronagraph design for minimum sensitivity to pointing jitter, (2) guide camera using the starlight reflected directly from the focal plane mask without positional bias, and (3) pointing correction with a dedicated fast/fine steering mirror control loop within the coronagraph instrument.

- ***Response to low order wavefront errors:*** (1) coronagraph design to minimize sensitivities to low order wavefront errors, where possible, (2) enable Zernike low order wavefront sensing by shaping the reflective phase of the focal plane mask, and (3) correction of low order WF drift using one of the DMs with a tight budget for open-loop DM surface control.

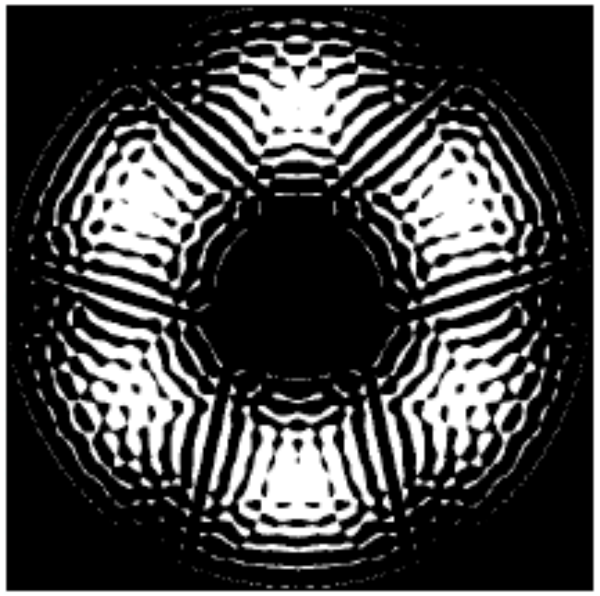
CGI coronagraph masks



HCL metal-dielectric mask (100 micron dia)



HLC Lyot stop

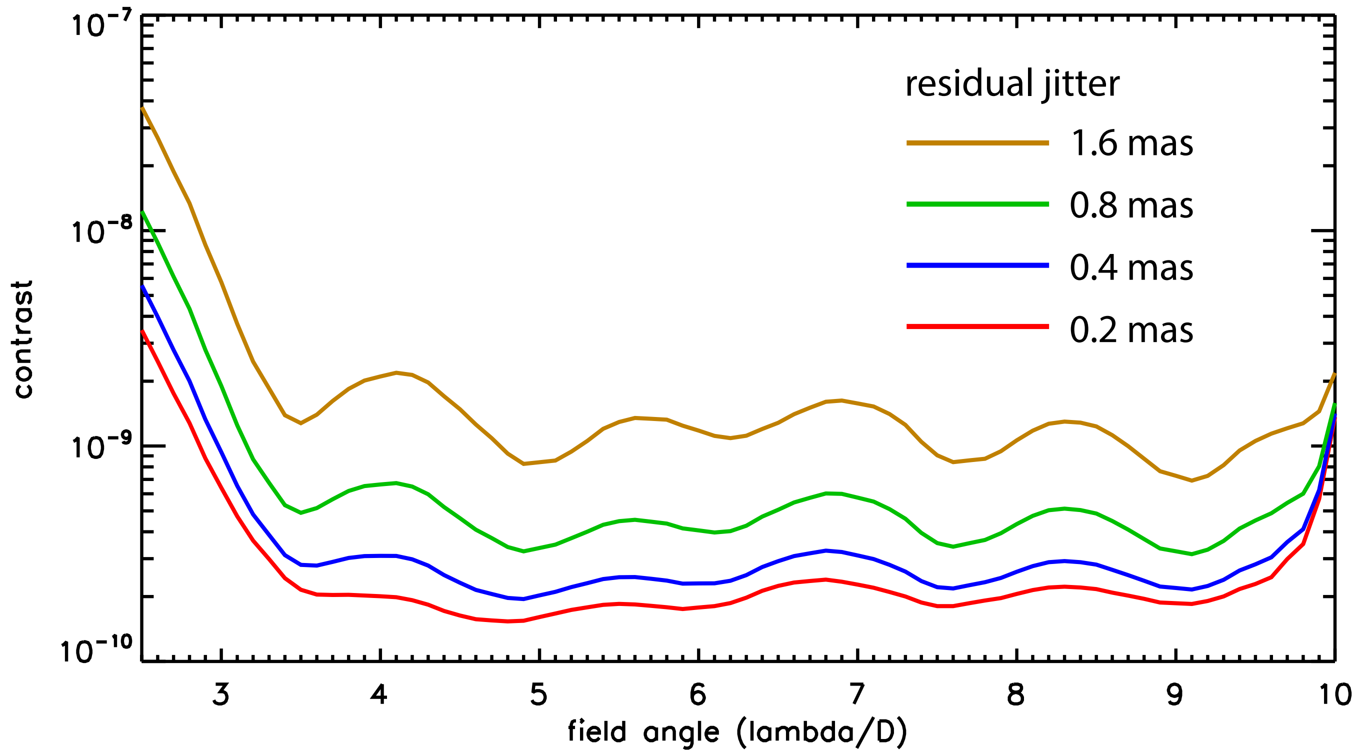


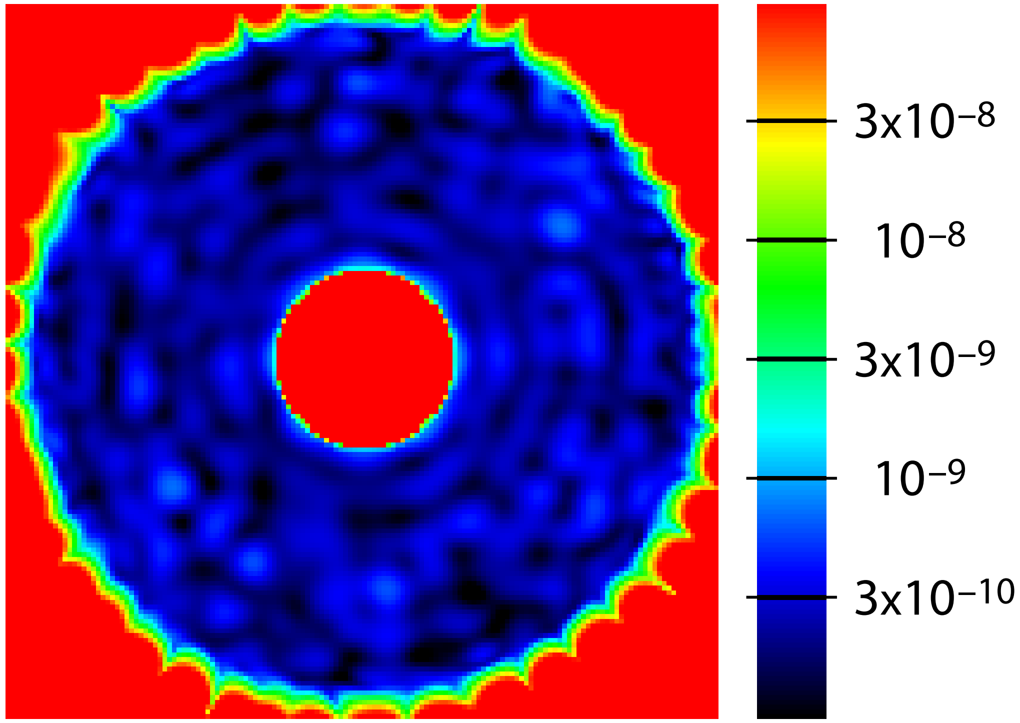
Shaped pupil mask for disk science

- Examples of focal plane and pupil plane elements for the hybrid Lyot (HLC) and shaped Pupil (SPC) coronagraph modes.
- HLC focal plane mask is comprised of two layers– one metal and one dielectric – to provide leverage over both the amplitude and phase (real and imaginary parts) of the incoming stellar PSF, fabricated by JPL's MicroDevices Laboratory.
- At center, superimposed in blue on a silhouette of the WFIRST pupil, the Lyot stop completes the HLC coronagraph.
- At right, one of several SPC masks, inserted into the optical path upstream of an opaque focal plane occulting mask, also fabricated by JPL's MicroDevices Laboratory.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Coronagraph high contrast dark field

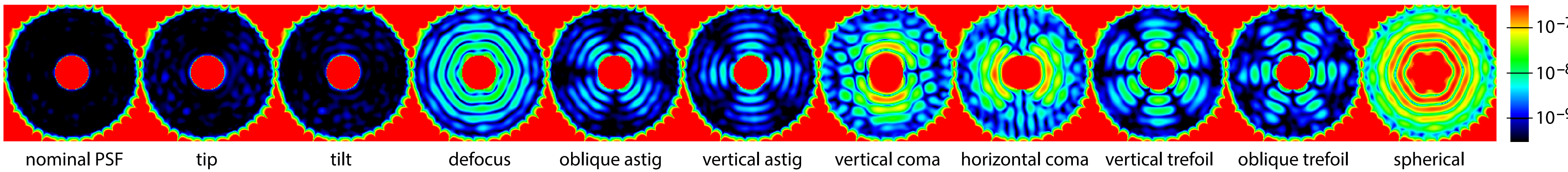




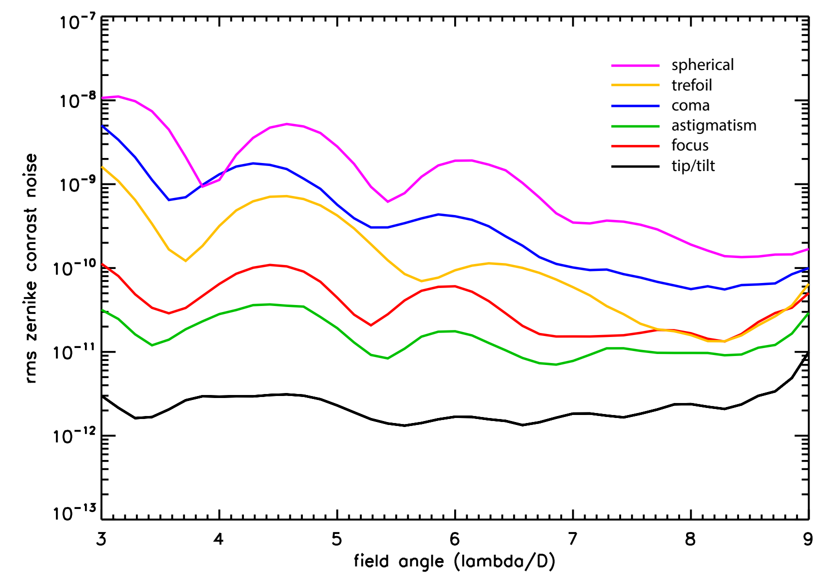
- HLC design optimization utilizes the ***focal plane mask, Lyot stop, and DM settings as free parameters.***
- High contrast dark field extends from ***2.8 to 10 λ/D in radius*** with ***10% spectral bandwidth*** centered on 550 nm.
- ***Full 360° field*** is optimal for initial imaging of RV planets and blind searches for new planets, where the orbital parameters are yet unknown.
- Design anticipates the expected range of ***residual pointing jitter*** in the WFIRST coronagraph. (Figure does not include other sources of wavefront error.)

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Coronagraph contrast sensitivity to low order wavefront drift



- Coronagraph design is tolerant to jitter, but sensitive to low order wavefront drift.
- Above, the appearance of dark fields (10% bandwidth, 0.4 mas rms jitter, 1 mas diameter star) in response to individual zernike wavefront errors of 100 pm rms introduced at the WFIRST primary mirror.



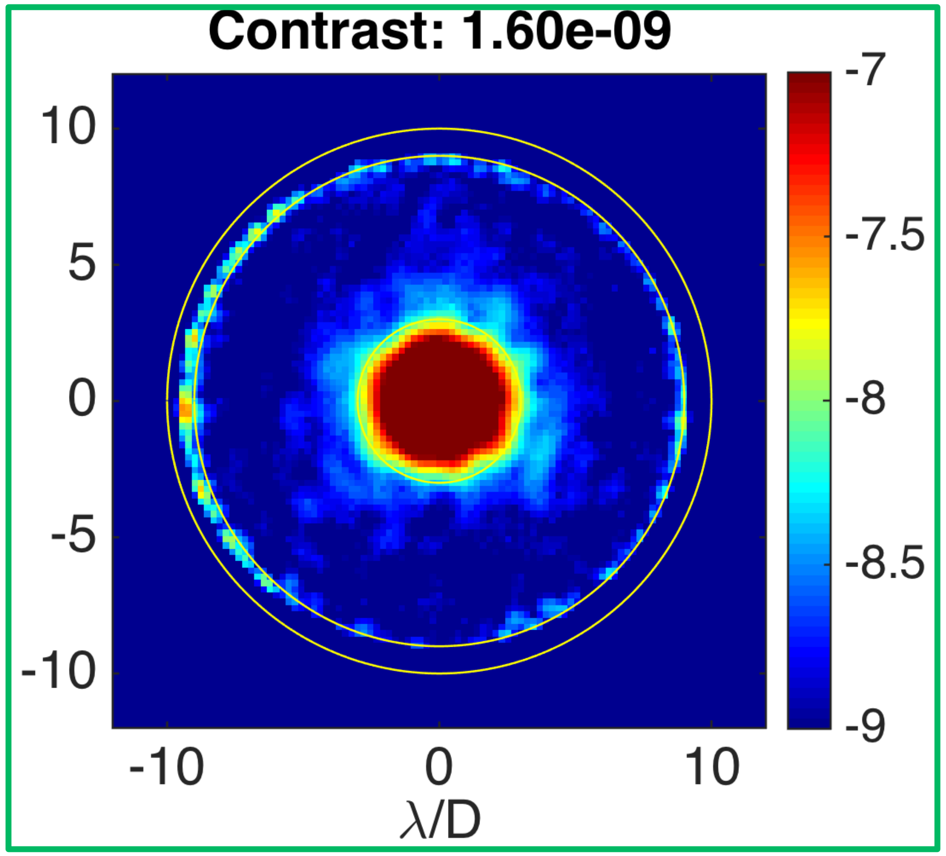
- Plotted at right are the rms azimuthal variations between aberrated and nominal PSFs vs. radial separation for each zernike term.
- Coronagraph will compensate for low order wavefront drift with a low order wavefront sensing and control (LOWFS&C) system.

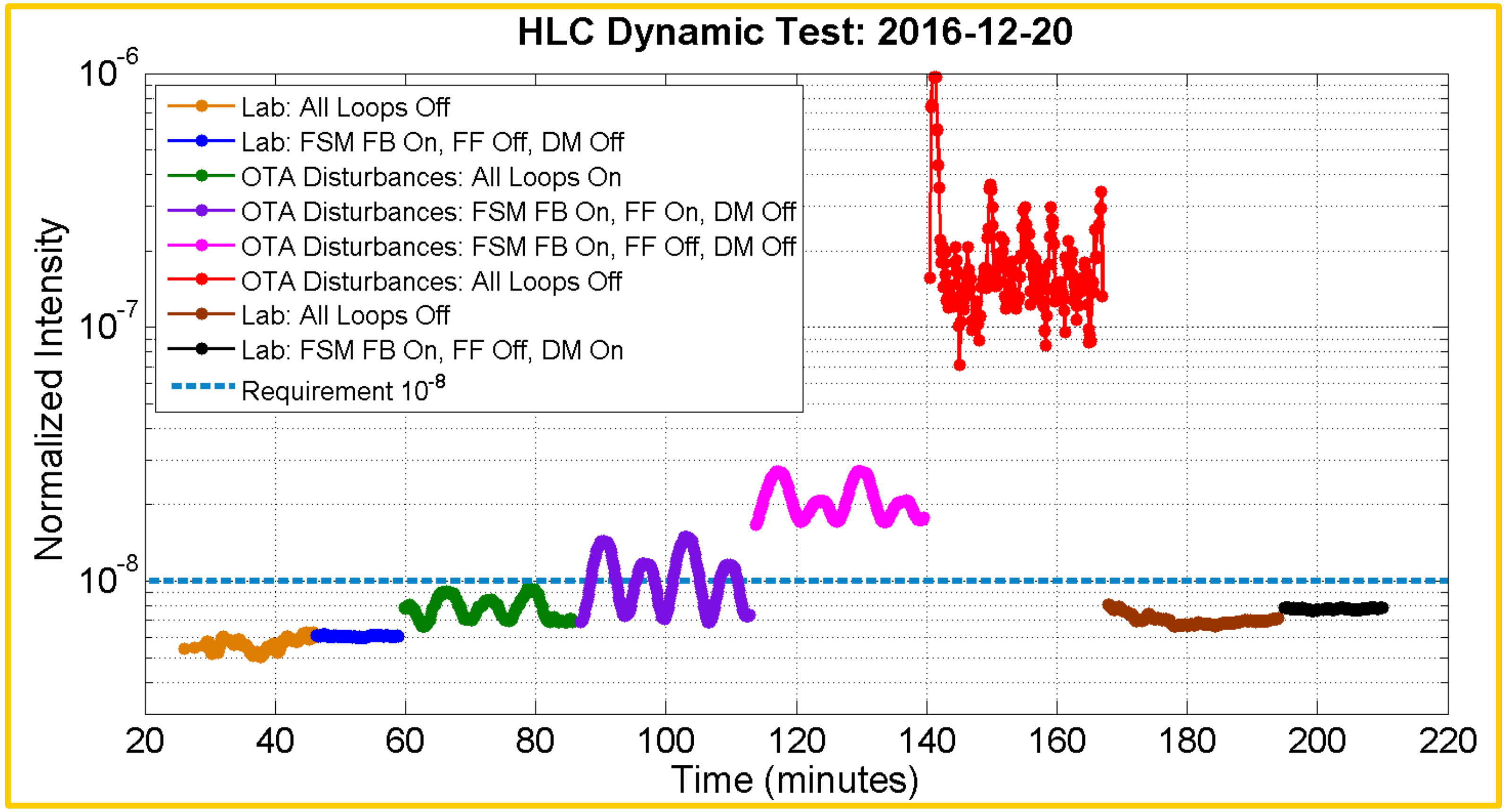
(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Coronagraph contrast demonstrations

- Ultimate objective of ongoing laboratory work is to bring ***demonstrated contrast performance into agreement with expectations*** from our detailed coronagraph models.
- Work is organized as a ***sequence of performance milestones***. To date, contrast better than $2x10^{-9}$ in 10% bandwidth has been achieved.
- ***Model fidelity is limited only by our knowledge*** of the optical characteristics, alignment, and stability of the coronagraph elements, since the well-understood physics of Fresnel wavefront propagation is not in question.
- Ongoing efforts are aimed at ***measuring, understanding, and correcting*** sources of stray light, ghost images, optical imperfections, misalignments, and jitter in the testbed components.

Coronagraph contrast demonstrations

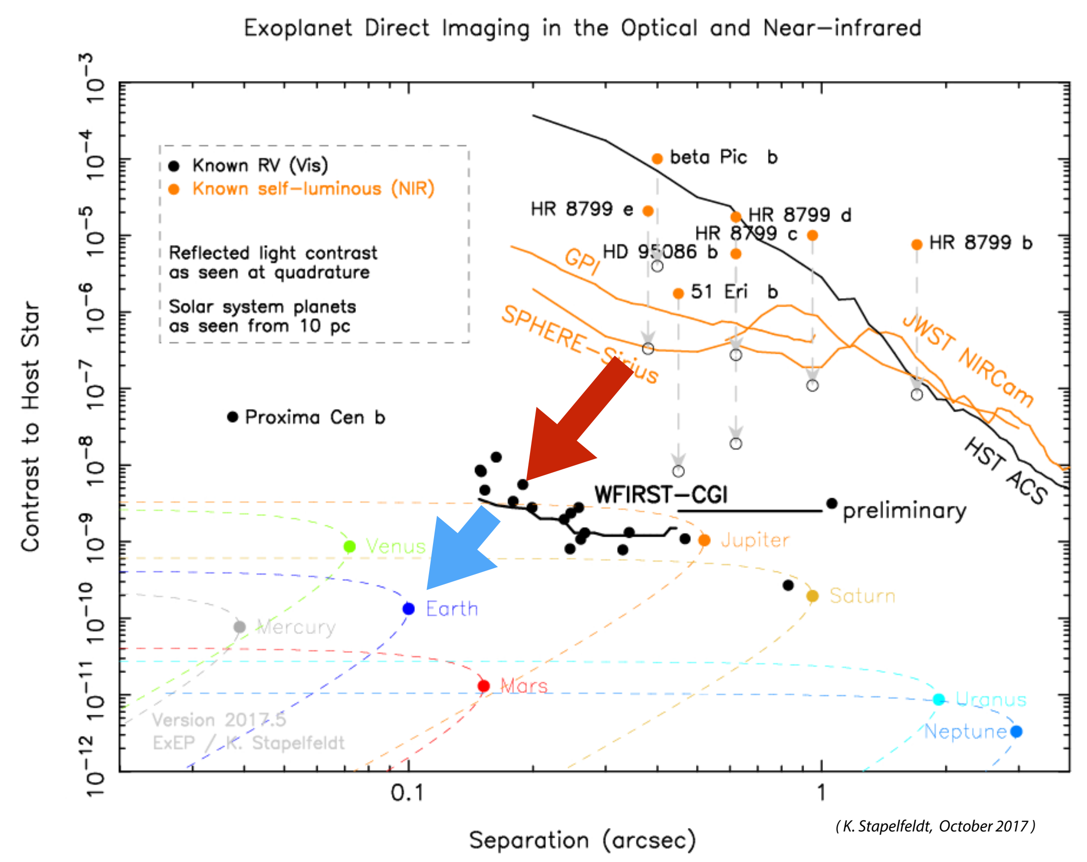


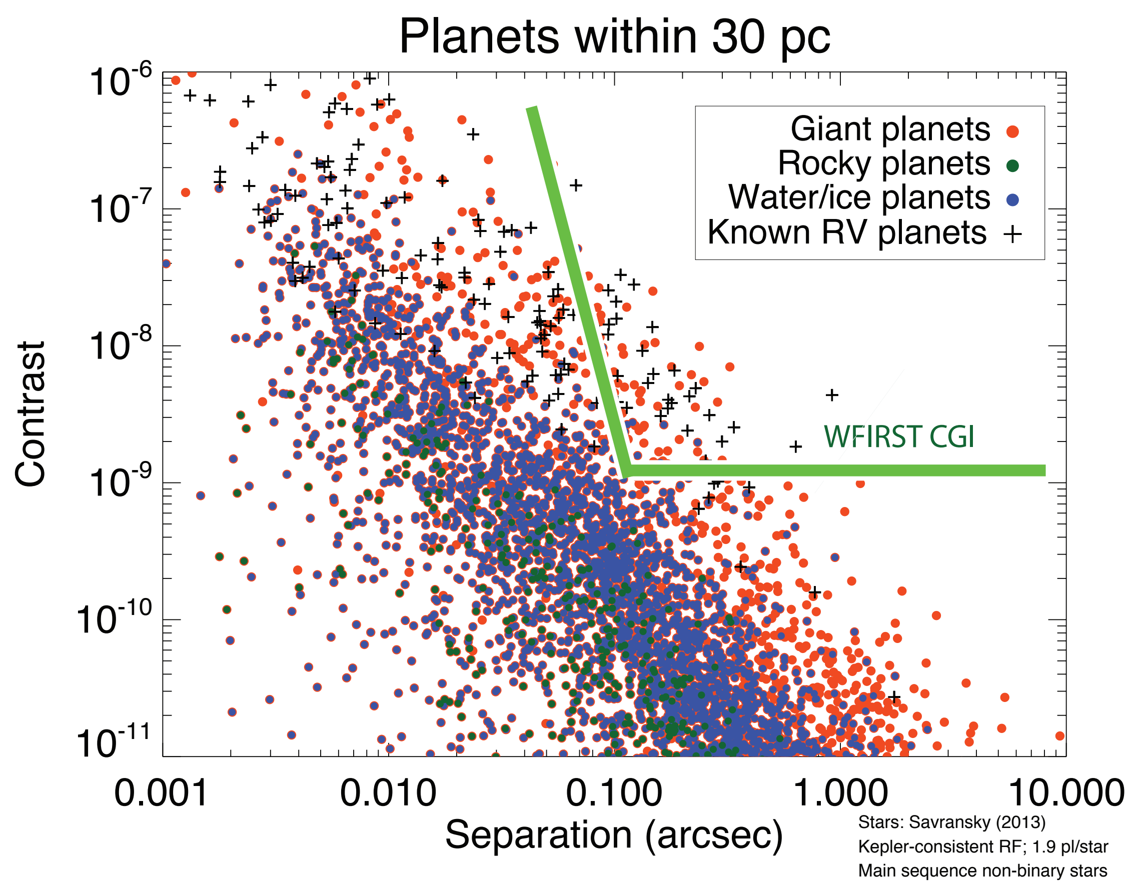


- HLC contrast laboratory demonstration on the WFIRST MCB testbed: 10% spectral bandwidth centered at 550 nm.
- At left, a ***demonstration of 1.6×10^{-9} contrast*** in the static testbed environment (J. Seo, 12/2016).
- At right, ***contrast in the dynamic testbed environment*** simulating on-orbit pointing and focus disturbances, and LOWFS&C sensing and rejection (F. Shi, 12/2016):
  - 14 mas rms pointing drift plus estimated WFIRST jitter corrected with a fast steering mirror,
  - 2 nm PV focus disturbance (4x worst than WFIRST expectations) corrected with the DM.

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

WFIRST Coronagraph Instrument is a pathfinder for a next-decade exo-Earth imaging mission





- *The WFIRST Coronagraph Instrument actualizes the Astro2010 Decadal recommendations for a* ***New Worlds Technology Development Program*** *and establishes a foothold in pioneering exoplanet science and technology.*
- *Performance of the AFTA coronagraph illuminates the pathways for advancement enabling the* ***next-decade exoplanet mission****: telescope size, stability, pointing, wavefront control, post-processing, etc.*

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

Summary

- Coronagraph design and post processing strategies will be matched to our best knowledge of the WFIRST telescope. Wavefront control is our greatest technical challenge.
- Laboratory demonstrations and characterizations of the essential wavefront control technologies are central to the WFIRST coronagraph development efforts at JPL.
- The WFIRST coronagraph is designed to provide our first images of mature exoplanets in reflected starlight, while its technology specifically addresses the Astro2010 recommendations for New Worlds Technology Development.

"I'll tell you something else I think. I think there are other bowls somewhere out there with intelligent life just like ours."

Frank Modell – The New Yorker – 11/2/1987

(J. Trauger, Mirror Tech Workshop, 11/16/2017)

End